Possible collapse of reef shark populations in remote coral reef ecosystems in the Coral Sea (Western Pacific)

by

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Abstract. – The decline of meso-predators such as reef sharks is a concern as such species can have important ecological roles in maintaining reef ecosystem resilience. Two field trips conducted in August 2010 and November 2011 to the Chesterfield archipelago (Coral Sea) allowed us to assess the abundances and average sizes of medium-bodied Carcharhinidae with a specific focus on grey reef shark (*Carcharhinus amblyrhynchos*), through fishing (46 hours of accumulated effort) and underwater visual censuses (25 hours of accumulated effort). We found low abundance and small average total length (TL) for all reef shark species, and in the case of the grey reef shark, an average abundance of 2.1 individuals/dive with the majority of animals less than 110 cm TL. We compared our findings with historical data and, given our low sampling effort, we so far hypothesise that a general strong decline in the reef shark populations may have occurred in this area, probably due to recent overfishing. The enforcement of conservation measures is strongly recommended among these remote reefs as well as complementary studies for confirming this hypothesis.

Received: 10 Nov. 2015
Accepted: 13 Jan. 2016
Editor: O. Otero

Résumé. – Effondrement potentiel des populations de requins de récif au sein d'écosystèmes récifo-coralliens isolés de la mer de Corail (Pacifique Ouest).

Le déclin de méso-prédateurs tels que les requins de récif pose problème dans la mesure où ces espèces peuvent avoir un rôle important dans le maintien de la résilience des écosystèmes coralliens. Deux missions conduites en août 2010 et novembre 2011 dans l'archipel des Chesterfield (mer de Corail) nous ont permis d'évaluer les abondances et longueurs totales (LT) moyennes de Carcharhinidae côtiers, en particulier du requin gris (*Carcharhinus amblyrhynchos*), à partir de sessions de pêche (46 heures au total) et de comptages sous-marins (25 heures au total). Nous avons globalement trouvé de très faibles abondances et tailles moyennes avec, spécifiquement pour le requin gris, une abondance moyenne de 2,1 individus/plongée et une majorité d'animaux avec des LT inférieures à 110 cm. Nous avons comparé ces résultats à des données historiques et, étant donné certaines limites de notre échantillonnage, nous nous cantonnons à poser l'hypothèse d'un déclin généralisé des populations de requins de récifs dans cette zone, probablement dû à la surpêche. La mise en œuvre effective de mesures de conservation est fortement recommandée au sein de ces récifs éloignés, de même que des études complémentaires pour confirmer cette hypothèse.

Key words
Carcharhinidae
Carcharhinus amblyrhynchos
Coral Sea
Meso-predators
Coastal
Overfishing
Population densities

The Coral Sea (Central Western Pacific), historically named for the vast amount of coral structures located within it (Room, 1997), is surrounded on its Eastern and Western side by the largest coral reef formations, the Australian Great Barrier Reef (GBR), and the world's largest coral lagoon of New Caledonia. The GBR was listed by UNESCO as a World Heritage site in 1981, while such classification was afforded to the New Caledonian lagoons in 2008, as a recognition of the exceptional and unique natural assets they contain. A large number of other coral structures exist in the Coral Sea, especially on the Australian side, such as Lihou Reefs, Marion Reefs or Frederick Reefs. Within the New Caledonian Exclusive Economic Zone (EEZ), major coral reefs of the main island and its lagoon are Entrecasteaux archipelago off the northern coast of Grande Terre, and the Chesterfield-Bellona plateaux off the northwestern coast of Grande Terre, about half way between New Caledonia and the Australian coastline (Fig. 1A).

Meso-predators such as coastal reef sharks (Hussey *et al*., 2014) are important for maintaining the stability and functional equilibrium among reef ecosystems (Heithaus *et al*., 2008; Baum and Worm, 2009; Ritchie and Johnson, 2009). Shark resilience among reef ecosystems is however limited by their very low fecundity and is also strongly linked to the genetic diversity among the connected diverse populations of conspecifics (Vignaud *et al.,* 2014). Given their central position in the Coral Sea, the Chesterfield-Bellona reefs complex is a remote and isolated place, where reef sharks could be vulnerable to overfishing with consequent loss of genetic variability. Nevertheless, some species of reef sharks can migrate several hundred kilometres, suggesting that these reefs may act as a stepping stones between large populations of reef sharks present in Australia and New Caledonia. Reef shark populations of the GBR and the Australian side of the Coral Sea are quite well documented (Robbins *et al.,* 2006; Heupel *et al.,* 2010; Barnett *et al.,* 2012; Espinoza

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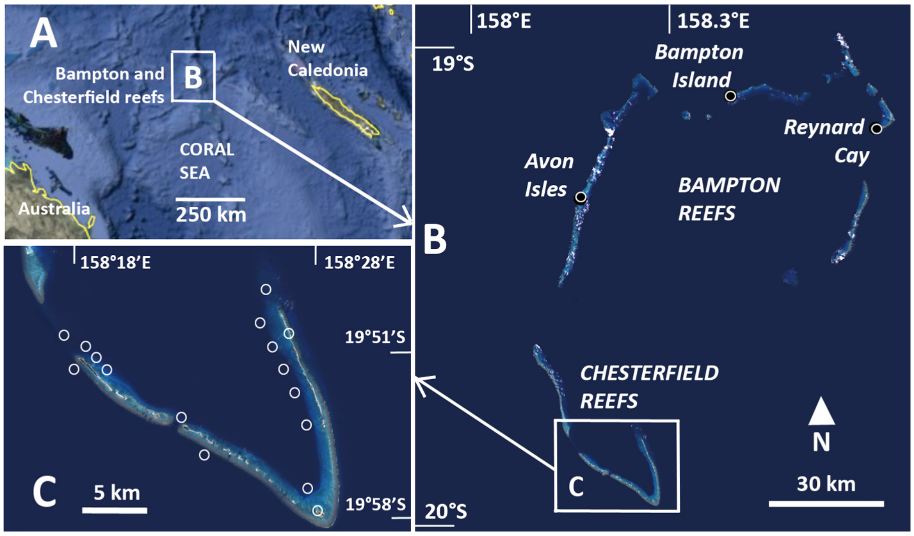

Figure 1. - **A**: Location of the Chesterfield and Bampton reefs in a central position among the Coral Sea, between the Australian Eastern coast and New Caledonia. **B**: Close up of the reefs where the 2010 and 2011 field trips were conducted; specific spots for shark surveys are shown with circles around the Bampton Reefs. **C**: Close up on the Chesterfield reefs with circles showing the locations for fishing and underwater visual surveys.

et al., 2015), but there has not been, so far, a single study focused on the reef shark populations of the Chesterfield-Bellona area.

In this study, we report on two field missions that focused on assessing the status of coastal reef shark populations in the Chesterfield archipelago (northern-west part of the Chesterfield-Bellona complex) in order to compare it with historical data. In spite of some sampling limitations, our results show enough consistency to hypothesise a significant decrease of reef shark abundances in this area of the central Coral Sea, that could serve as baseline and promote further investigations.

MATERIAL AND METHODS

Location of the study site and logistics

The Chesterfield-Bellona complex is part of the Lord Howe Ridge that runs northwest from the South Island of New Zealand, separating the Tasman Sea from the Fijian Sea. This ridge originated from the movement of the Indo-Australian plate (Slater and Goldwin, 1973; Andrefouet *et al*., 2009), which then led to the merging of volcanic structures, which subsequently collapsed. This subsidence phenomenon allowed the creation of enormous atoll structures, with the Chesterfield and Bampton reefs delineating a wide open lagoon with a surface area of 3,500 km^2, between latitudes 19°00' and 20°00' South and longitudes 158°10' and 159°00' East (Fig. 1B). The lagoon is made of diverse plateaux located at different depths that are scattered with coral pinnacles, which sometimes extend almost to the surface. For these characteristics, sailors gave the Chesterfield and Bampton reefs its reputation of the "world's most inaccessible reefs" (Godard, 1982). Indeed, this area has never been hydrographically surveyed and remains one of the world most dangerous areas for ship navigation with multiple wrecks occurring during the 19th century (Guillou, 1983).

Two field missions were conducted on 11-18 August 2010, and 18-25 November 2011 (excluding travel from and to New Caledonia). They were both based on large vessels equipped with appropriate smaller motorized vessels (between 4 to 5 meters long) for allowing scuba diving and fishing. The 2010 field trip focused on the Chesterfield reefs, between 19°51' and 19°58' South and 158°18' and 158°28' East, at a distance of about 500 miles from Nouméa (Fig. 1C). This area is built upon a barrier reef with a V-shape, oriented northwest/southeast, each leg is about 25 km long. This barrier is open to the ocean on the northeast side, and is interrupted by two passes in the west; the northern one is large (about 5 km wide and more than 50 m deep in its centre), "L'île Longue Pass", the southern one being narrower (less than 1 km wide and about 20 m deep), named "L'îlot du Passage Pass" (Fig. 1C). This semi-continuous barrier constitutes the only efficient shelter for boats from the dominant southeast swell. The second field trip in 2011 encompassed the Bampton Reefs (with stops in Reynard, Bampton and Avon islands) and a final stop in the Chesterfield reefs (Fig. 1B, C).

Data collection and analysis

The main objective of the missions was to tag large tiger sharks, and the staff spent most of their time on that task. However, during both missions, up to two operators dedicated some of their time to fishing for smaller-bodied reef sharks, either from the beaches of several islets (water depth ranged from 0 to 1.5 m) to target juveniles, or from a boat (water depth 10 to 25 m) to capture adults. All fishing sessions were performed in coral reef environments, composed of sandy bottoms with reef patches. Every session involved baiting with dead fish thrown in the water every five minutes

to attract and concentrate the reef sharks. Baits used on the lines were discards of tuna [*Thunnus albacares* (Bonnaterre, 1788)], wahoo [*Acanthocybium solandri* (Cuvier, 1832)] and diverse fresh reef fishes that were purposely caught during the fishing session. Light drumlines with metal traces and barbless circle hooks were baited with similar pieces of fish and used for restraining the sharks. Additional details, such as sampling effort and location of fishing sites, are provided in table I. In 2010, a single operator accumulated a total of 25 hours of fishing with two lines in four different areas (from two different islands, and from the boat in the lagoon and in the pass/outer reef). In 2011, two operators with one fishing line each accumulated a total of 21 hours of fishing in 12 different zones around five islets, with the same fishing protocol (Tab. I). As the water transparency always allowed it, the behaviour (boldness-shyness) of the sharks toward the baited hooks was also systematically assessed during all fishing sessions.

As a complementary approach, data were collected underwater on the number of reef sharks seen per dive by scientific divers during each of two expeditions to the Chesterfield archipelago. Scuba diving was given priority, but as the capacity for refilling tanks was limited, free diving was also used in order to count reef sharks. The planning of diving was organized in order to allow at least one scuba dive per site, and once tanks were empty, free diving was utilized. As they were opportunistic, free dives were of different durations but results were standardised (per hour) through the sampling effort. In 2010, several scuba dives were conducted by two operators. The two operators were diving together, side by side, without any baiting, and visually assessing the sharks (for species, length and sex when possible) to the limit of visibility. In addition, two free diving sessions (duration: 1 hour) were organized. In order to concentrate the sharks present in a given area, a freediver was in charge of spearing fishes to attract the sharks while the other one was counting sharks. Altogether, the accumulated underwater effort was 20 hours of visual counting. In 2011, an effort of 2 hours of scuba diving was implemented in three different sites. They were complemented by two hours and 20 min of free diving in six different sites, including lagoons, reef passages and outer slopes (Tab. II). For each dive, sharks were numbered and abundances were calculated by dividing the total number of sharks by the effort (duration of the dive in hours), including a standard deviation (SD) for averages.

Table I. - Date, location (including GPS coordinates) and effort of the fishing sessions during the 2010 (AF) and 2011 (BF) field trips, respectively. A distinction is made between fishing from the beach of an islet or from the boat.

Sessions	Date	Island	Effort (h)	From	Long.	Lat.
#AF1	11/08/10	Long	4	Beach (lagoon side)	19°52'00	158°18'41
#AF2	12/08/10		4	Boat	19°51'42	158°19'19
#AF3	13/08/10		4	Beach (West)	19°52'20	158°18'31
#AF4	14/08/10		3	Passage	19°51'19	158°18'05
#AF5	15/08/10	Loop	4	Beach (lagoon side)	19°58'09	158°28'37
#AF6	17/08/10	Anchorage	3	Beach (ocean side)	19°53'16	158°28'23
#AF7	18/08/10		3	Beach (ocean side)	19°54'11	158°23'05
#BF1	18/11/11	Reynardt	1.5	Beach	19°12'46	158°55'52
#BF2	19/11/11		1.5		19°12'47	158°55'53
#BF3		Bampton	1	Boat	19°07'17	158°35'26
#BF4			2	Beach	19°07'33	158°36'06
#BF5	20/11/11		2	Beach	19°12'33	158°36'26
#BF6			2.5	Boat	19°07'57	158°35'58
#BF7	21/11/11	Avon North	6		19°30'38	158°14'45
#BF8			1	Beach	19°30'44	158°15'00
#BF9	22/11/11		1	Boat	19°30'59	158°14'57
#BF10	23/11/11	Anchorage	1.6	Beach	19°53'03	158°28'16
#BF11	24/11/11		0.5		19°53'36	158°28'30
#BF12		Passage	0.5	Boat	19°54'35	158°22'27

Acquisition of comparative data

No scientific publications have been produced about reef shark species and their abundances at the Chesterfield reefs, but anecdotal information exists, mostly through testimonies and magazine articles. Before and after the missions, we gathered all available documentation and we interviewed several reliable people, both in New Caledonia and Australia, who had diving experience at the Chesterfield reefs.

As complementary data, we also used the data provided by fishing sessions in other locations in the Pacific, using the same techniques and implemented by the same operators. We then compared the average catch per unit of effort (CPUE) of blacktip sharks [*Carcharhinus melanopterus* (Quoy & Gaimard, 1824)] during fishing sessions in New Caledonia (Grande Terre) and French Polynesia, plus the size distribution of grey reef sharks [*C. amblyrhynchos* (Bleeker, 1856)] caught in Moorea Island (French Polynesia) through a similar fishing effort (25 hours). The grey reef sharks caught were allocated to size classes and a one-way Mann-Whitney *U*-test (Sokal and Rohlf, 1995) was used to compare the median sizes of sharks from the two campaigns. The null hypothesis (H_0) states that there is no difference between the median sizes of the two groups of sharks, while the alternative hypothesis (H_1) says that the median size of Polynesian sharks is greater than that

Table II. - Date, location (including GPS coordinates) and effort of the diving sessions during the 2010 (AF) and 2011 (BF) field trips, respectively. A distinction is made between scuba and free diving, with a mention of the average and maximum depth during each dive, and with or without the use of attractive stimulus (mainly speared live fishes). The average depth does characterize the place where observations were made, not the diving performance.

Sessions ID	Date	Island	Effort (h)	Location	Type of diving	Ave.-max depth (m)	Long.	Lat.
#AD1	11/08/10	Long	4	Passage	Scuba	15-20	19°51’01	158°18’03
#AD2	12/08/10		2	Lagoon	Scuba	10-15	19°51’44	158°18’54
#AD3	13/08/10		1	Lagoon	Free	10-15	19°52’28	158°19’45
#AD4	14/08/10		2	Outer slope	Scuba	25-60	19°52’28	158°17’48
#AD5	15/08/10	Passage	2	Passage	Scuba	20-22	19°54’31	158°22’22
#AD6	16/08/10		1	Outer slope	Free	10-15	19°55’05	158°22’27
#AD7		None	4		Scuba	20-22	19°56’06	158°24’25
#AD8	17/08/10	Loop	3	Lagoon	Scuba	15-18	19°57’13	158°28’01
#AD9	18/08/10	Anchorage	1	Lagoon	Scuba	10-15	19°51’54	158°26’50
#BD1	18/11/11	Reynardt	1	Passage	Free	15-20	19°13’20	158°56’23
#BD2	19/11/11	Bampton	0.8	Outer slope	Scuba	25-36	19°13’21	158°56’24
#BD3	20/11/11		1.5	Lagoon	Free	02-10	19°07’09	158°32’59
#BD4			0.66	Outer slope	Scuba	15-23	19°06’34	158°33’25
#BD5	21/11/11	Avon North	0.25	Outer slope	Free	0-20	19°30’36	158°14’54
#BD6			1	Lagoon	Free	0-8	19°30’48	158°15’04
#BD7	23/11/11	Anchorage	0.3	Lagoon	Free	0-10	19°53’25	158°27’46
#BD8	24/11/11		0.25	Passage	Free	0-15	19°48’15	158°25’31
#BD9	25/11/11	Long	0.66	Lagoon	Scuba	3-8	19°52’00	158°18’58

for Chesterfield Islands. The choice of a one-tailed alternative hypothesis is based on our assumption of intensive shark fishing in the Chesterfield, which is likely to have deceased the median shark size, whereas shark fishing in Moorea has never been intensive.

RESULTS

Assessment of shark abundances through fishing

During the 2010 field survey, a total of 19 reef sharks were caught. This total was composed of 12 grey reef sharks with an average TL of 109 ± 14 cm, four blacktip reef sharks (*C. melanopterus*) with an average TL of 105 ± 30 cm, two whitetip reef sharks [*Triaenodon obesus* (Rüppell, 1837)] with an average TL of 105 ± 5 cm and one 90 cm TL silvertip shark [*C. albimarginatus* (Rüppell, 1837)] (Tab. III).

During the 2011 field trip, a total of 39 reef sharks were captured. This total was composed of 22 grey reef sharks with an average TL of 100 ± 33 cm, 15 blacktip sharks with an average TL of 121 ± 20 cm, two whitetip reef sharks with an average TL of 120 ± 20 cm

Table III. - Shark catches per fishing sessions, with a mention of the gender and species of shark and an assessment of the average total length per species, with the standard deviation (SD).

Sessions	Number of blacktip	Number of grey reefer	Number of silvertip	Number of whitetip
#AF1	1F	2F+1M	0	0
#AF2	0	6F	0	0
#AF3	0	0	0	0
#AF4	0	0	1F	2F
#AF5	2M + 1F	1F	0	0
#AF6	0	0	0	0
#AF7	0	0	0	0
Av. size (cm)	105	109	90	105
SD (cm)	*30*	*14*	*0*	*5*
#BF1	2F + 1M	1F	0	0
#BF2	0	0	0	0
#BF3	0	9F	0	0
#BF4	1M	2F	0	1F
#BF5	0	0	0	0
#BF6	0	5F	0	0
#BF7	0	5F	0	0
#BF8	1F	0	0	1M
#BF9	0	0	0	0
#BF10	6F + 1M	0	0	0
#BF11	2F + 1M	0	0	0
#BF12	0	2F	0	0
Av. size (cm)	100	121	0	120
SD (cm)	33	20	0	20

Table IV. - Catch Per Unit of Effort (CPUE) of blacktip shark *Carcharhinus melanopterus* in different locations of New Caledonia and French Polynesia, respectively. Fishing efforts (in hours) varied but the fishing technique was similar (handline with wired trace holding a baited barbless hook). The CPUE are presented by decreasing order in column 5.

Country	Location	Number of sharks	Fishing effort (h)	CPUE (shark/h)	Source
French Polynesia	Acteon archipelago	234	52	4.50	Clua (2009)
	Rangiroa atoll	37	14	2.60	Vignaud (2008), unpubl. data
	Fakahina atoll	42	37	1.10	Mourier *et al*. (2009)
New Caledonia	Mato islet	12	15	0.80	Vignaud and Clua (2010), unpubl. data
	Chesterfield reefs	4	25	0.16	Present study

(Tab. III). The site close to North Avon Island was significantly different from all other sites in terms of shark densities, having quick catches and intense feeding frenzies (NB: one grey reef shark was cannibalized by conspecifics on a fishing line that was not retrieved soon enough; EC, Pers. Obs.).

Most of the blacktip sharks were juveniles with a TL around 60 cm, and they were found in shallow waters around the beachrocks, in particular in a nursery at the south end of the northern-most Mouillage islets (Fig. 1C).

Comparison of CPUE and size

The CPUE of blacktip shark during the 2010 field trip was 0.16 shark/h. This CPUE is far below those registered on the Grande Terre of New Caledonia (0.8 shark/h) or even the lowest registered in French Polynesia in Fakahina atoll (1.1 shark/h) where CPUE came up to 4.5 shark/h in the remote Acteons archipelago (Tab. IV).

Regarding the size of grey reef sharks caught with similar techniques and effort, an obvious difference exists between the results obtained in Moorea (French Polynesia) with a mean size around 160 cm TL (n = 9) compared to 110 cm TL in the Chesterfield Islands (n = 12). Based on the number of shark among the 10 size classes, this difference in favour of Moorea was assessed as highly significant ($P < 0.001$) by the Mann-Whitney one-tailed test ($W = 103.5$, p-value = 0.0002) (Fig. 2).

Behaviour of the sharks toward baited hooks

Avoidance behaviour was obvious with all sharks, but particularly for the grey reef sharks. Observation recorded the sharks circling around the baited hook, eating the pieces of fish that were used to chum around the hook, but very rarely taking it. When a shark came close to the hook, attracted by the bait, it would often abruptly turn away at the last moment. However, such a shyness was not observed on the outer slope of Avon North Islet during the first fishing session on the 19 November 2011 (see BF3 session in Tabs I, III).

Table V. - Shark observations per diving sessions during the 2011 field trip, with a mention of the species and the average total length per species (assessed through visual census). Significant numbers of sharks with sizes above 120 cm TL were only found at BD5 (North Avon Islet) for which densities and sizes were far above the rest of the Bampton and Chesterfield reefs.

Sessions	Species	Number	Length (cm)
#BD1	Whitetip	1	100
#BD2	Grey	2	110
#BD3	0	0	0
#BD4	Grey	2	90
		1	100
		1	110
#BD5		> 20	100-140
#BD6		2	110
#BD7		1	110
#BD8	Whitetip	1	120
#BD9	0	0	0

Underwater Visual Surveys (UVC)

During the 2010 field survey, UVC of reef sharks accumulated a total of 49 individuals composed of 38 grey reef sharks with an average estimated TL of 110 ± 22 cm (maximum observed size of 160 cm TL), five blacktip reef sharks with an average TL of 130 ± 20 cm (maximum observed size of 150 cm TL), two whitetip reef sharks with an average TL of 105 ± 5 cm (maximum observed size of 160 cm TL) and five silvertip shark with a maximum observed size of 120 cm TL. The average shark abundance was of 2.0 sharks per dive.

Regarding the shark average abundance assessed during the 2011 field survey, figures should not be generalised as one area hosted significantly higher densities than the others. This specific area was on the outer slope of Avon North Islet where, in accordance with high CPUE in this same spot (see BF3 session in Tabs I, III), a single school of more than 20 grey reef sharks was observed in 15 min, with individuals ranging from 100 to 140 cm TL. The eight other spots allowed the observation of 12 individuals composed of 10 grey reef sharks with an average TL of 110 ± 22 cm (maximum observed size of 160 cm TL), and two whitetip reef sharks with an average TL of 105 ± 5 cm (maximum

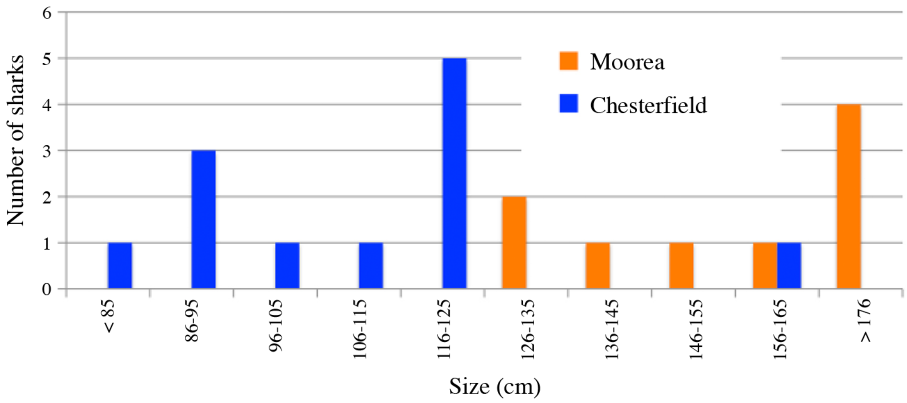

Figure 2. - Number of grey reef shark (*C. amblyrhynchos*) per size classes caught in Moorea Island (French Polynesia) and Chesterfield Islands reefs (New Caledonia), respectively, with similar techniques and fishing effort (25 h × 1 operator). The size difference was assessed as highly significantly ($P < 0.001$), and greater in Moorea than in the Chesterfield, by a one-tailed Mann-Whitney *U*-test.

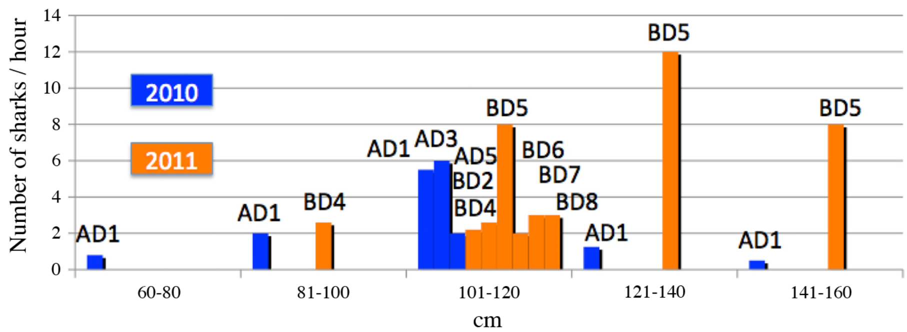

Figure 3. - Comparison of average sizes of grey reef shark (*C. amblyrhynchos*) assessed through underwater visual censuses during the 2010 (blue) and 2011 (orange) field trips. In order to facilitate the comparison, shark numbers were linked to effort (h). Sizes above 120 cm TL are essentially represented by the assessment in BF3 spot (North Avon Islet) for which densities and sizes were far above the rest of the Bampton and Chesterfield reefs.

observed size of 160 cm TL) (Tab. V). Excluding the Avon North assessment, the average shark abundance was of 2.2 sharks per dive.

Gathering the UVC results from both 2010 and 2011 field trips shows that the average TL of the majority of grey reef sharks ranged from 100 to 120 cm (Fig. 3). Some larger animals were rarely observed, most of them being in the area of North Avon (see BD5 session in Tabs II, V).

Comparative data from the Chesterfield reefs and similar environments

A skin diving mission was organized in 1971 to the Chesterfield reefs by an Australian team composed of several skilled divers, including the well-known Ron and Valerie Taylor (Harding, 1971). According to the magazine article, sharks were found in 'very high densities, and not used to seeing human beings'. Here are some quotations from the article: "Nobody suspected that shark activity would be as intense as it was…", "The Chesterfield sharks were aggressive, not simply curious…", "The sharks were inquisitive and swam very close to us", "These sharks appeared to be starved, they attacked the propellers on our small boats and swam excitedly around, breaking the surface with their dorsal fins", "… It was just a matter of throwing a baited hook into the water, within half a minute it would hook a 15 pound Red Bass. Before that fish could be brought out of the water a shark would have it.", "The sharks were so hungry that once they grabbed hold of that bait they would not release their vice-like grip until they had been dragged completely clear of the water. One shark even swam out of the water and on to the exposed reef while following the bait being drawn a few inches ahead…". An interview of V. Taylor by EC in June 2010 in Cairns, during the Sharks International Conference, confirmed impressive concentrations of reef sharks in the Chesterfield, in accordance with the magazine article by Harding *et al*. (1971). Several other oral testimonies confirmed a very high density of reef sharks between the 1970's and 1980's. Pierre Laboute is a former scientific diver for IRD (formerly ORSTOM) that undertook several missions in the area (Rancurel *et al*., 1973; Richer de Forges *et al*., 1986, 1988). Following a mission that took place between the 21 and 28 June 1973, he wrote the following comment in the mission report about his diving experience: "*Carcharhinus menissorah* (NB: former scientific name for *C. amblyrhynchos*)… and *C. albimarginatus*… swim together and form… on the outer slope an impassable 'barrier', and if you try to cross it, their number increases substantially and very quickly" (see p. 10 *in* Rancurel *et al*., 1973). During an interview about the shark density around Chesterfield reefs, he orally added this specific comment: "During one of these missions that took place around April, I remember that we were witnessing the hatching of small green turtles (*Chelonia mydas*), when we have been surrounded by several hundreds of grey reef sharks (*Carcharhinus amblyrhynchos*), close to

the île Longue, in a depth of around 30 meters. They were very excited. We actually had to jump back on the boat, and some sharks twice bit the propeller of the boat as it was running; it was unbelievable…" Testimonies about more recent experiences (2008) do not describe such concentrations but still mention a very high concentration and presence of reef shark during each dive (G. Lasne, Pers. Comm.).

DISCUSSION

The data collected through the two 2010 and 2011 missions in Chesterfield reefs appear consistent and suggests the hypothesis of a possible collapse of reef shark populations in this area. However, the scope of our study must be expanded and suggestions for improving our knowledge of the situation regarding reef sharks in these remote reefs deserve to be promoted.

Potential caveats in our sampling methodology

As previously mentioned, the methodology used during both missions through fishing and underwater visual assessment both in scuba and free diving, was implemented on an opportunistic and time- limited basis. However, the methods we used are well defined and have been implemented in other places in the Pacific on the same shark species, allowing reliable comparisons of CPUE (see Figs 2, 3). The diving methodology mixed scuba and free diving, two quite different sampling methods, but in our experience we believe that in such remote coral reef ecosystems, both methods usually allow proper assessment of the resident sharks. Most of the time, bubbles produced by scuba diving attract rather than repel the reef sharks (E. Clua, Pers. Obs.) and are even used by professionals for better approaching them underwater (Heyman *et al*., 2001). Scuba diving is a widely used technique for underwater visual assessment of sharks (Ward-Page *et al*., 2010). As free diving does not include the bubble stimulus, by spearing fishes we have been using another acoustic stimulus, based on the low frequency sound waves produced by wounded fishes, that is a strong booster for attracting surrounding sharks (Myrberg, 1978).

Notwithstanding any potential bias, consistent use of the same techniques across multiple sites allows a legitimate comparison of relative abundance (Craik, 1981). Therefore, in spite of a low sampling effort and given the proven reliability of the sampling methods, we propose a hypothesis about the status of reef shark populations in the considered area.

Low abundances for Chesterfield reef sharks and avoidance behaviour

Reef shark CPUE depends on shark density, but also on their behaviour in presence of fishing gear. As mentioned in the 'Results' section, avoidance behaviour was obvious with all sharks, particularly for grey reef sharks. It is known that sharks can detect metal, but are not afraid of it until they experience being caught, or see other individuals being caught (Spaet *et al.,* 2010). This behaviour suggests that the grey reef sharks of the Chesterfield have experienced fishing with heavy gear (i.e. metal traces and large hooks) in the recent past. This avoidance behaviour is not unique to the Chesterfield, and does not compromise comparisons among regions using the same fishing gear. In addition to strong avoidance behaviour, the low CPUE (see Fig. 2) can be explained by a low density of sharks. We sometimes spent more than one hour chumming before the first shark showed up. Regarding the CPUE registered for blacktip shark (Tab. IV), they are definitely far below any other data collected elsewhere in the Pacific with similar fishing techniques.

Underwater, no more than six sharks were seen together at the same time during the 2010 field trip. Through both missions our findings of average abundances of 2.0 and 2.2 sharks per dive are consistent with those of Graham *et al*. (2010) in remote atolls of the Indian Ocean where the number of sharks observed per scientific dive declined over 90% from a mean of 4.2 in the 1970s to 0.4 in 2006. It is however relevant to mention the contrasting situation found around Avon North Islet, where a very high density of grey reef sharks was encountered, leading to intra-specific depredation among this species, as already described in such situations (Clua *et al.,* 2014).

Small average size for Chesterfield reef sharks

Besides being low in abundance, Chesterfield sharks globally had small average sizes, which is a well-known effect of overfishing (Bradshaw *et al.,* 2008). The average and maximum sizes of the grey reef shark recorded in the Chesterfield were always under 160 cm TL. This species can reach a maximum size of 220 cm TL (Compagno, 2001). In a remote place such as Chesterfield, as far as it is quite pristine, we could expect to catch or observe some large animals (usually females) (Friedlander and De Martini, 2002); but none were observed. It does not mean that none are present in the area, but they must be in low densities. While the catching of small size sharks could be an artefact of fishing sampling methods, it is improbable to only observe small sized reef sharks underwater if larger ones are supposed to be sharing the same habitat, as it was shown for the reef shark species that we were targeting during both missions (Speed *et al*., 2011).

Potential overfishing of Chesterfield reef shark populations

The combination of low abundances and average sizes of animals allows us to hypothesise that Chesterfield reef

sharks have been fished in the recent past. It seems that most of the large adults were fished a few years before 2010 and 2011 and that we only observed the juvenile sharks, which escaped from the fishing. While boats from New Caledonia do not target sharks, our hypothesis is strongly supported by the proven occurrence of illegal shark fishing in the area by foreign vessels. The most convincing example is a Taiwanese boat that was arrested in May 2007 by the French navy in the Bellona area, a few tens of miles from The Chesterfield with a load onboard of seven tons of sharks and 25 tons of bait dedicated to longline fishing (Anonymous, 2007).

The same comments about probable overfishing of adult animals can be made about the whitetip shark *C. albimarginatus*, as all sighted individuals were young animals, even in the pass of île Longue, which has a strong oceanic influence that is favourable for attracting large sharks from this species. The fact that one place (BF3 - North Avon Islet) hosted much higher densities and large sharks compared to all other spots through both field trips, can be seen as indirect proof for such an hypothesis. Given the similarity of environmental parameters between Avon Islets and the rest of Bampton reefs, the difference could be explained by the fact that no fishing was implemented in this specific area, for whatever reason. We saw however very young grey reef sharks, probably born in 2010, which means there are probably still some adults mating in the area (cf. Tab. V).

These present abundances and size distributions are comparable to heavily fished areas in the Pacific or the Caribbean (Sandin *et al.,* 2008; Ward-Paige *et al.,* 2010), and the sharks' behaviour suggests that they have been experiencing very heavy longline fishing. Therefore, the risk of witnessing a local extinction, such as described in a remote archipelago from the Atlantic Ocean (Luiz and Edwards, 2011) should be considered.

The need for additional data collection

As a group, sharks are susceptible to even mild levels of fishing mortality given their late age of maturity, slow growth, and slow reproductive rate (Myers and Worm, 2005). A recent study conducted on the Australian side of the Coral Sea showed that high residency and limited spatial use of semi-isolated reef might contribute to a higher vulnerability of reef sharks to targeted fishing pressure (Barnett *et al.,* 2012). This vulnerability might be worsened in the case of the Chesterfield reefs, as the connectivity with other populations of conspecifics might be even lower due to the isolation of the place (Espinoza *et al.,* 2015). If so, new migrants (in a position to input genetic diversity in the local population) are probably very rare, and a depleted population would take a long time to recover. In the longer term, the loss of genetic diversity may alter the resilience of their local populations and indirectly the resilience of adjacent populations of conspecifics that will not be able to benefit from any genetic connectivity and genes exchanges through the migration of some individuals, as has been shown for the grey reef shark on the Great Barrier Reef (Heupel *et al.,* 2010). The historical spatial and genetic connectivity at a sub-regional level might be then jeopardized by such a depletion of reef shark populations in potential bridging reefs of the Coral Sea.

Since April 2013, the Chesterfield archipelago has been included in waters where shark fishing is now banned by the New Caledonian government. The health of the Chesterfield reefs will strongly depend on the efficiency of enforcing these conservation measures for both pelagic and reef sharks, probably by better controlling the presence and activity of boats in this area. In the meanwhile, it is recommended to organise complementary DNA sampling campaigns in the area to enable genetic analysis aiming to determine the connectivity and resilience of the local reef shark populations.

Acknowledgements. – This study was organized under the auspices of the Secretariat of the Pacific Community and through the Coordination Unit of the Coral Reef Initiatives for the Pacific (CRISP Programme) based in Noumea, New Caledonia, and benefited from a financial support by the Agence Française de Développement (AFD). For technical help, the authors wish to thank Jonathan Werry (Griffith University), Maël Imirizaldu (independent consultant) and Céline Barré (independent consultant) in the framework of the reef shark studies conducted in the Chesterfield and Bampton Reefs. We also thank Malcolm Francis (Niwa, New Zealand) and Pierre Legendre (University of Montreal) who contributed to the improvement of the paper.

REFERENCES

ANDREFOUET S., CABIOCH G., FLAMAND B. & PELLETIER B., 2009. - A reappraisal of the diversity of geomorphological and genetic processes of New Caledonian coral reefs: a synthesis from optical remote sensing, coring and acoustic multibeam observations. *Coral Reefs*, 28: 691-707.

ANONYMOUS, 2007. - Palangrier taïwanais : du requin plein les cales. *Les Nouvelles Calédoniennes*, édition du 16 mai 2007.

BARNETT A., ABRANTES K.G., SEYMOUR J. & FITZPATRICK R., 2012. - Residency and spatial use by reef sharks of an isolated seamount and its implications for conservation. *PLoS ONE* 7(5): e36574.

BAUM J.K. & WORM B., 2009. - Cascading top-down effects of changing oceanic predator abundances. *J. Anim. Ecol*., 78: 699-714.

BRADSHAW C.J., FITZPATRICK B.M., STEINBERG C.C., BROOK B.W. & MEEKAN M.G., 2008. - Decline in whale shark size and abundance at Ningaloo Reef over the past decade: the world's largest fish is getting smaller. *Biol. Conserv.*, 141(7): 1894-1905.

CLUA E., 2009. - Campagne de prélèvements (17 au 28 mars 2009) de matériel génétique sur requins du genre *Carcharhinus* dans le cadre de la mission "archipel des Actéons". 13 p. Rapport technique du CRISP.

CLUA E., GALVES J.B. & WERRY J.M., 2014. - Insight into cumulative intra-guild and intra-specific depredation among sharks. *Cybium*, 38(4): 311-313.

COMPAGNO L.J.V., 2001. - Sharks of the World. An Annotated and Illustrated Catalogue of Shark Species Known to Date. Vol. 2. Bullhead, mackerel and carpet sharks (Heterodontiiformes, Lamniformes and Orectolobiformes). FAO Species Catalogue for Fisheries Purposes, 1(2): 1-269.

CRAIK G., 1981. - Underwater survey of coral trout *Plectropomus leopardus* (Serranidae) populations in the Capricornia section of the Great Barrier Reef Marine Park. *Proc. of the 4th Int. Coral Reef Symp.*, Manila, Philippines, 1: 53-58.

ESPINOZA M., HEUPEL M.R., TOBIN A.J. & SIMPFENDORFER C.A., 2015. - Residency patterns and movements of grey reef sharks (*Carcharhinus amblyrhynchos*) in semi-isolated coral reef habitats. *Mar. Biol.*, 162(2): 343-358.

FRIEDLANDER A.M. & DE MARTINI E.E., 2002. - Contrasts in density, size, and biomass of reef fishes between the north western and the main Hawaiian Islands: the effects of fishing down apex predators. *Mar. Ecol. Prog. Ser.*, 230: 253-264.

GODARD P., 1982. - Les Chesterfield : l'île la plus proche du Paradis. Nouméa : Éditions d'Art Calédoniennes. (non paginé)

GRAHAM N.A., SPALDING M.D. & SHEPPARD C.R., 2010. - Reef shark declines in remote atolls highlight the need for multi-faceted conservation action. *Aquat. Conserv.: Mar. Freshw. Ecosyst.*, 20(5): 543-548.

GUILLOU J., 1983. - Trois naufrages aux îles Chesterfield au siècle dernier. *Bull. Soc. Etud. Hist. Nouvelle-Calédonie*, 55: 27-46.

HARDING J., 1971. - A skin diving expedition to the remote Chesterfield reefs. *Fathom Mag.*, 6: 7-23.

HEITHAUS M.R., FRID A., WIRSING A.J. & WORM B., 2008. - Predicting ecological consequences of marine top predator declines. *Trends Ecol. Evol.*, 23: 202-210.

HEUPEL M.R., SIMPFENDORFER C.A. & FITZPATRICK R., 2010. - Large-scale movement and reef fidelity of grey reef Sharks. *PLoSONE*, 5(3): e9650.

HEYMAN W.D., GRAHAM R.T., KJERFVE B. & JOHANNES R.E., 2001. - Whale sharks *Rhincodon typus* aggregate to feed on fish spawn in Belize. *Mar. Ecol. Prog. Ser.*, 215: 275-282.

HUSSEY N.E., McNEIL M.A., McMEANS B.C., OLIN J.A., DUDLEY S.F.J., CLIFF G., WINTNER S.P., FENNESSY S.T. & FISK A.T., 2014. - Rescaling the trophic structure of marine food webs. *Ecol. Lett.*, 17(6): 239-250.

LUIZ O.J. & EDWARDS A.J., 2011. - Extinction of a shark population in the Archipelago of Saint Paul's Rocks (Equatorial Atlantic) inferred from the historical record. *Biol. Conserv.*, 144(12): 2873-2881.

MOURIER J., VIGNAUD T. & PLANES S., 2009. - Rapport de la mission requin à Fakahina. 8 p. Rapport CRIOBE pour le service de la pêche.

MYERS R.A. & WORM B., 2005. - Extinction, survival or recovery of large predatory fishes. *Phil. Trans. R. Soc. B*, 360: 13-20.

MYRBERG A.A., 1978. - Underwater sound-its effect on the behavior of sharks. *In*: Sensory Biology of Sharks, Skates and Rays (Hodgson E.S. & Mathewson R.F., eds), pp. 391-417. Washington DC: US Government Printing Office.

RANCUREL P., LABOUTE P. & SCHMID M., 1973. - Compte rendu de mission aux îles Chesterfield du 21 au 28 juin 1973 : annexe 1. Compte-rendu des plongées: annexe 2. Florule des îles Chesterfield. 13 p. multigr. Nouméa: ORSTOM.

RICHER DE FORGES B., LABOUTE P. & MENOU J.-L., 1986. - La campagne Musorstom 5 aux îles Chesterfield : N.O. "Coriolis", 5-24 octobre 1986. Rapports scientifiques et techniques, 41. 31 p. multigr. Nouméa: ORSTOM.

RICHER DE FORGES B., CHEVILLON C., LABOUTE P., BARBIGANT G., MENOU J.-L. & TIRARD P., 1988. - La campagne Corail 2 sur le plateau des îles Chesterfield (N.O. "Coriolis" et N.O. "Alis", 18 juillet au 6 août 1988). 70 p. multigr. Sciences de la mer, Biologie marine, Rapports scientifiques et techniques, 50. Nouméa: ORSTOM.

RITCHIE E.G. & JOHNSON C.N., 2009. - Predator interactions, mesopredator release and biodiversity conservation. *Ecol. Lett.*, 12: 982-998.

ROBBINS W.R., WILLIAM D., HISANO M., CONNOLLY S.R. & CHOAT J.H., 2006. - Ongoing collapse of coral-reef shark populations. *Curr. Biol.*, 16: 2314-2319.

ROOM A., 1997. - Placenames of the World: Origins and Meanings of the Names for over 5,000 Natural Features, Countries, Capitals, Territories, Cities, and Historic Sites. 441 p. Jefferson, NC: Mc Farland.

SANDIN S.A., SMITH J.E., DEMARTINI E.E. *et al.* [19 authors], 2008. - Baselines and degradation of coral reefs in the Northern Line Islands. *PLoS ONE*, 3(2): e1548.

SLATER R.A. & GOODWIN R.H., 1973. - Tasman sea guyots. *Mar. Geol.*, 14: 81-99.

SOKAL R.R. & ROHLF F.J., 1995. - Biometry – The Principles and Practice of Statistics in Biological Research. 3rd edit. 887 p. New York: W.H. Freeman.

SPAET J.L., KESSEL S.T. & GRUBER S.H., 2010. - Learned hook avoidance of lemon sharks (*Negaprion brevirostris*) based on electroreception and shock treatment. *Mar. Biol. Res.*, 6(4): 399-407.

SPEED C.W., MEEKAN M.G., FIELD I.C., McMAHON C.R., STEVENS J.D., McGREGOR F., HUVENEERS C., BERGER Y. & BRADSHAW C.J.A., 2011. - Spatial and temporal movement patterns of a multi-species coastal reef shark aggregation. *Mar. Ecol. Prog. Ser.*, 429: 261-275.

VIGNAUD T.M., MOURIER J., MAYNARD J.A., LEBLOIS R., SPAET J., CLUA E., NEGLIA V. & PLANES S., 2014. - Blacktip reef sharks, *Carcharhinus melanopterus*, have high genetic structure and varying demographic histories in their Indo-Pacific range. *Mol. Ecol.*, 23: 5193-5207.

WARD-PAIGE C.A., MORA C., LOTZE H.K., PATTENGILL-SEMMENS C., McCLENACHAN L., ARIAS-CASTRO E. & MYERST R.A., 2010. - Large-scale absence of sharks on reefs in the Greater-Caribbean: a footprint of human pressures. *PLoS ONE*, 5(8): e11968.